Monitoring of European Corn Borer with Pheromone-Baited Traps: Review of Trapping System Basics and Remaining Problems

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J. Econ. Entomol. 100(6): 1797–1807 (2007)

ABSTRACT Since the identification of female European corn borer, *Ostrinia nubilalis* (Hübner) pheromone, pheromone-baited traps have been regarded as a promising tool to monitor populations of this pest. This article reviews the literature produced on this topic since the 1970s. Its aim is to provide extension entomologists and other researchers with all the necessary information to establish an efficient trapping procedure for this moth. The different pheromone races of the European corn borer are described, and research results relating to the optimization of pheromone blend, pheromone bait, trap design, and trap placement are summarized followed by a state-of-the-art summary of data comparing blacklight trap and pheromone-baited trap techniques to monitor European corn borer flight. Finally, we identify the information required to definitively validate/invalidate the pheromone-baited traps as an efficient decision support tool in European corn borer control.

KEY WORDS monitoring, mesh cone trap, sticky trap, water pan trap, blacklight trap

Since Klun and Brindley (1970), Klun and Robinson (1970), and Klun et al. (1973) succeeded in identifying the sex pheromone released by European corn borer, *Ostrinia nubilalis* (Hübner), females, traps baited with a synthetic blend mimicking the female pheromone are regarded as a tool to monitor this pest (Roelofs et al. 1972, Klun et al. 1973, Showers et al. 1974, Kochansky et al. 1975). Despite the emergence of genetically modified *Bacillus thuringiensis* (Bt) corn, European corn borer control is still largely based upon insecticides or the use of biological agents. These control methods include pyrethroid insecticides, various *B. thuringiensis* formulations, and the oophagous parasitoid wasps *Trichogramma* spp., all of which target specific life stages. Pyrethroid and Bt formulations mainly kill neonate larvae before their tunneling into corn, *Zea mays* L. stalks or ears, and the *Trichogramma* wasp kills only the eggs laid by the moth on the host plant leaves. Thus, the timing of treatment application is a key factor for the success of a control strategy against European corn borer (Nault and Kennedy 1996), and treatment should be applied when most of the European corn borer population in the field is composed of the targeted instar. To achieve coordination between the treatment schedule and pest phenology, farmers require real-time information concerning the European corn borer population. Blacklight traps (BLTs) can provide such information. Plotting the daily capture of adult moths indicates both the onset of adult emergence and the flight peak, which are key points in European corn borer phenology to infer egg deposition and first instar activity. However, there are major limits to their use by corn growers and extension agents. First, BLTs require a power source, and they are difficult to handle in the field. Second, because of the lack of trap specificity, it is necessary to sort the European corn borer individuals from among other trapped species, which is time-consuming and may prove difficult if species of similar morphology are present. Other methods for European corn borer monitoring consist of scouting fields for European corn borer egg masses on host plant leaves, looking for European corn borer damage symptoms (shot-holed leaves and tunneled stalks; methods summarized in Hudon et al. 1989), or counting adults in grassy borders (Sappington and Showers 1983). These scouting methods are associated with unavoidable disadvantages, because they require a strong and repeated sampling effort and consequently they are time-consuming and expensive.

The disadvantages of both BLT trapping and field scouting justify investigation of the sex pheromone-baited traps (PBTs) as an alternative method to assess European corn borer phenology. The principle of sex pheromone-baited traps is to specifically attract European corn borer males by using a synthetic pheromone mimicking the female pheromone and then capture these males. By counting daily or biweekly capture of males, it should be possible to plot a flight curve assumed to describe the moth population dynamics and to use it in a predictive way to anticipate both the peak of egg laying by European corn borer females and the average egg hatch period.

After the description of the female sex pheromone of European corn borer as a binary blend of Z-11

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tetradecenyl acetate (Z11-14:Ac) and E-11 tetradecenyl acetate (E11-14:Ac) in a ratio 97:3 (Z race) (Klun et al. 1973) or 4:96 (E race) (Kochansky et al. 1975), investigations focused on developing trapping systems composed of a lure (also referred to as bait, i.e., a dispenser releasing the synthetic pheromone to attract European corn borer males) and a trap designed to catch the attracted males. Numerous studies have been performed in areas where European corn borer damages corn and other crops. However, until now, no synthesis has been made of 30 yr of investigations into developing a pheromone trapping system for European corn borer. In the two main reviews dedicated to the European corn borer (Gahukar and Chiang 1976, Hudon et al. 1989), both the monitoring of adult activity and the potential of synthetic pheromone in mating disruption are cited, but problems in using pheromone-baited traps are not discussed. Gahukar and Chiang (1976) mention with almost no detail the effect of pheromone composition, lure type (e.g., rubber caps versus polyethylene caps), and trap shape, whereas Hudon et al. (1989) mainly focuses on the results obtained through blacklight trap, scouting techniques, and drop net catch of adults in aggregation sites.

Because PBTs are still being used for European corn borer monitoring and other purposes as diverse as management of resistance to genetically modified corn (Showers et al. 2001, Bontemps et al. 2004, Qureshi et al. 2005), pheromone strain survey (Bontemps et al. 2004, Sorenson et al. 2005), and pheromone perception understanding (Gemeno et al. 2006), we aimed this review at providing useful information for optimum trapping of the European corn borer. The present review is the first synthesis made from the huge body of work dedicated to this topic. After a description of the pheromone races in European corn borer, the main results obtained with pheromone trapping are presented with particular regard to the optimization of the pheromone lure, the trap design, and finally trapping procedures, including trap placement. The technique of pheromone trapping is then compared with the blacklight trap technique, and finally, the "competition" hypothesis and topics that require further investigation are highlighted and discussed.

Pheromone Race in European Corn Borer

Like many moths, European corn borer females signal to mate-seeking males by releasing a volatile sex pheromone derived from fatty acids and produced by a gland located on the abdomen tip (Ma and Roelofs 2002). The composition of this pheromone was first described in the early 1970s by Klun and Brindley (1970) and Klun and Robinson (1970), who showed that European corn borer females emit an unsaturated carbonated chain—Z11-14:Ac—which is biologically active on males. European corn borer males submitted to this volatile component at short range display typical mating behaviors, such as wing fanning, clasper display, and copulation attempts. However, the full description of the female European corn borer sex pheromone was yet to come. A few years later, Klun et al. (1973) and Kochansky et al. (1975) discovered the biological importance of minor amounts of the E isomer of Δ11-14:Ac. By means of trapping experiments on European corn borer males and analysis of extracts from female abdomen tips, they demonstrated that the fully active pheromone is not just the Z11-14:Ac molecule but instead binary blend composed of both the Z- and E11-14:Ac stereoisomers. Z- and E11-14:Ac are both required for maximum attraction of European corn borer males. Two pheromone strains have been identified: the Z strain, with females emitting and males responding to a "Z" blend with the Z isomer as the major component (97%) and the E isomer as a minor component (3%), and the E strain in which females emit and males respond to an "E" blend with the opposite proportions of the Z isomer (3–1%) and E isomer (97–99%) (Kochansky et al. 1975). Hybrid individuals obtained by crossing these strains classically express an hybrid phenotype, with an intermediary blend of female pheromone composition—35% Z11-14:Ac and 65% E11-14:Ac, hereafter referred to as the "hybrid" blend—and an intermediary window of pheromone response for males (≈50% of males reaching the pheromone source in a wind tunnel when E11-14:Ac ranges from 3 to 65%, as shown by Glover et al. 1991). Zhu et al. (1996) found that some hybrids release a slightly different blend, with ≈85% of the E isomer on average.

Based on results from pheromone trapping and female pheromone analysis, it has been shown that the Z strain is most prevalent in the world and that the two strains can live either allopatrically or sympatrically. The Z strain, present in Iowa (Klun et al. 1973) and thus sometimes referred to as the Iowa strain, is also present in Ontario, Canada (Kochansky et al. 1975), and most parts of North America and Europe (for overviews, see Klun and Cooperators 1975, Anglade et al. 1984). The E strain is present in the United States in New York state (Roelofs et al. 1985), Pennsylvania (Klun and Cooperators 1975), western Massachusetts (Fletcher-Howell et al. 1983), South Carolina (Durant et al. 1995), and North Carolina (Sorenson et al. 2005), whereas in Europe it is present in Switzerland (Buechi et al. 1982, Anglade et al. 1984, Peña et al. 1988), Italy (Anglade et al. 1984, Peña et al. 1988), The Netherlands (Roelofs et al. 1985), Greece (Y. Thomas, unpublished data) and France (Anglade et al. 1984, Thomas et al., unpublished data; Pelozuelo et al. 2004). In France, it is worth noting that the E pheromone was identified exclusively from individuals feeding on hops, *Humulus lupulus* L. (Cannabinaceae) or mugwort, *Artemisia vulgaris* L. (Asteraceae) host plants. Thus, the E strain coincides with a host race feeding on hop/mugwort and genetically differentiated from the Z strain populations feeding on corn (Thomas et al., unpublished data; Pelozuelo et al. 2004).

Other pheromone-like components have been regularly identified on the pheromone gland surface, particularly tetradecyl acetate (Kochansky et al. 1975, Klun and Junk 1977, Attygale et al. 1987, Struble et al.

1987, Peña et al. 1988, Kalinova et al. 1994, Pelozuelo et al. 2004), E-11 hexadecenyl acetate (E11-16:Ac) (Peña et al. 1988), and Z-11 hexadecenyl acetate (Z11-16:Ac) (Peña et al. 1988, Pelozuelo et al. 2004). However, because both Z- and E11-16:Ac and 14:Ac induce a significant electroantennographic response when puffed on the male antenna (M. Renou, personal communication), their behavioral relevance, if any, is still unknown.

Optimization of Pheromone Bait

Optimization of Pheromone Composition and Dose. After the description of the Z and E races and their hybrids (Klun et al. 1973, Kochansky et al. 1975, Cardé et al. 1975), the most important concern relating to the pheromone lure was determination of the pheromone blend to be used as bait in each particular location. Many authors have determined the races present in their own areas (see Pheromone Race in European Corn Borer). They also have looked for putative geographical variations in the attractive pheromone blend. Early articles showed that small variations in the pheromone blend have critical effects on captures. Deleting the minor isomer drastically reduces captures (Klun et al. 1973, Kochansky et al. 1975, Cardé et al. 1975, Kalinova et al. 1994) and using off-ratio blends also give lower catches. At sites where the hybrid blend was compared with the Z or E blends for attractiveness, it generally achieved worst results than the blend of the locally dominant race (Kennedy and Anderson 1980; Webster and Cardé 1984; Durant et al. 1986, 1995; Kalinova et al. 1994). The intermediate 50%/50% blend was also less efficient than typical Z and E blends in situations where Z and E strains, respectively, were prevalent (Cardé et al. 1975, Kennedy and Anderson 1980, Durant et al. 1986). Modifying the Z blend, Bartels et al. (1997) tested ratios ranging from 0.6 to 5.1% E11-14-Ac and found a strong attraction of Z males with blends ranging from 2.3 to 3.0% E11-14:Ac, whereas attraction was significantly reduced as soon as the E isomer proportion reached 5.1%. Additional investigations focused on compounds other than Z- and E11-14:Ac. Stockel (1980) found that male attraction was doubled in the presence of the saturated compound 14:Ac, although Kalinova et al. (1994) could not confirm such an effect. The Z11-16:Ac added to the Z blend did not positively affect captures when tested by Peña et al. (1988).

The Z- and E11-14:OH compounds, which are presumed to be generated by the degradation of the Z- and E11-14:Ac from the pheromone lure, were not found to significantly reduce male attraction when associated with the standard blend (McLeod and Starratt 1978), nor was dodecenyl acetate (12:Ac) in the same study. After efforts to determine the pheromone blend that should be used, the effect of using analogs or pheromone-like compound was tested (Schwarz et al. 1989, Klun et al. 1997). The study of structure–activity relationship by Schwarz et al. (1989) did not show any analog to be useful for male attraction, although some analogs are detected by male antennae (Fescemyer and Hanson 1990, Klun et al. 1997), and Klun et al. (1994, 1997) showed that fluorinated compounds can mimic pheromonal activity, but that they are not more efficient than the Z/E11-14:Ac blend. It is noteworthy that some studies tried to associate the European corn borer pheromone bait with others allelochemicals. Phenylacetaldehyde (PAA), which is a vegetal volatile compound released by corn plants, was tested as a putative synergist or coattractant of the pheromone (Maini and Burgio 1990). These authors showed that a cap loaded with PAA attracts female moths into traps at a low but significant level (0.98–1.05 females per trap per wk) and that it does not repel males from a pheromone-baited cap when used simultaneously. Based on these results, the authors tested a monitoring strategy using traps baited with both the pheromone lure and the kairomone lure together (Maini and Burgio 1999). They concluded that such multibaited traps, by allowing the simultaneous counting of males and females, "can be a better monitoring tool than the standard single-bait pheromone trap." Recently, Gemeno et al. (2006) showed that the European corn borer sex pheromone and *Sesamia nonagrioides* (Lefebvre) pheromone cannot be mixed in the same lure, because 10% of *S. nonagrioides* pheromone induces a significant reduction in European corn borer catches.

Investigations regarding the appropriate pheromone dose to use in the pheromone dispenser have given variable results. Gahukar and Chiang (1976) reported that doses lower than 100 μg are more efficient, but without indicating the origin of such information. McLeod and Starratt (1978) compared doses 25, 100, 250, 700, and 750 μg, and they concluded that 100 μg was the most efficient dose. From of a similar range—10, 50, 100, and 500 μg—Kalinova et al. (1994) showed that the 10-μg dose was more efficient than 100 μg. In practice, major firms producing pheromone lures for European corn borer trapping propose rubber caps loaded with 100 μg of the synthetic pheromone (confirmed by Trécé and Hercon customer services).

Optimization of Pheromone Dispenser. Most of the European corn borer female pheromone dispensers used to attract male moths are rubber caps loaded with the synthetic sex pheromone in pentane or hexane solution, the solvent being subsequently allowed to evaporate. Few studies have been dedicated to the dispenser itself. Gahukar and Chiang (1976) claim that rubber caps perform better than polyethylene caps, but they do not provide references or results to support this assertion. The information may have come from Roelofs et al. (1972) where rubber caps were shown to be more efficient at luring males than polyethylene caps. A later article (Kalinova et al. 1994) also demonstrated that red or brown rubber caps were more efficient than red, white, and transparent polyethylene caps. However, gray rubber caps had a similar low efficiency to transparent polyethylene caps. The reticulation level of the rubber was shown to influence the release of the sex pheromone and consequently its attractiveness (Stockel 1980).

Because some version of commercial and home-made lures had been reported to be unsuccessful at attracting European corn borer males (Cardé et al. 1975, Bartels et al. 1999), their efficiency was specifically tested by some researchers. Problems in the formulation of the sex pheromone blend could occur and explain this initial failure. This can be suspected due to the impossibility of obtaining pure Z- or E11-14:Ac product through synthesis, because small amounts of the opposite isomer are always coproduced and must be separated a posteriori by delicate high-pressure liquid chromatography. However, increased efforts to improve the pheromone formulation process and the higher sensitivity of the new generation gas chromatographs (used to check final Z/E11-14:Ac ratio) have led to a situation where there is little or no significant differences between brands (i.e., Zoecon versus Albany Inc.; Hercon versus Trécé; Durant et al. 1986, Bartels et al. 1999) and home-made lures (Mason et al. 1997, Bartels et al. 1999). However, due to the tightly tuned response of European corn borer males, the correct blend formulation is always a putative cause one has to consider when a trapping campaign fails to produce any significant capture.

Effect of Pheromone Dispenser Age. Aging of the pheromone dispenser has been studied as a possible cause of trapping failure. Trap users often report a decrease in capture after the trap has spent 1 wk in field conditions and an increase in capture when both bait and trap are replaced (Starratt and McLeod 1976, McLeod and Starratt 1978, Kennedy and Anderson 1980, Muszkat and Melamed-Madjar 1987, Kalinova et al. 1994). Thus, either a decreased attractiveness of the lure itself with age or a decreased efficiency of the trap at capturing attracted males may be suspected. Starratt and McLeod (1976) speculated that an inhibitor or repellent compound may form and adsorb onto sticky traps. Soon after, McLeod and Starratt (1978) showed that capture decrease involved a combined effect of both lure aging and sticky trap aging. However the putative repellent molecule was not identified. Because Kalinova et al. (1994) did not observe a capture decrease between first and second week of trapping when they used virgin European corn borer females as bait, such a repellent may come from the dispenser rather than the pheromone itself. In a wind tunnel, 2-wk-old pheromone caps were shown to be as attractive as brand new caps (Pelozuelo 2004).

Using water pan traps, Gray et al. (1991) found that changing the pheromone bait every 1, 2, or 3 wk had few effects on capture. However, they recommended weekly lure replacement for best survey of moth flight.

Optimization of Trap Design

After advances in Lepidoptera pheromone identification and synthesis allowed mimicking of moth pheromones, a limiting factor in moth trapping was the appropriate trap design to capture males. Among the numerous trap designs available (Cardé and Elkinton 1984), bucket traps, sticky traps, mesh cone traps, and water pan traps (Fig. 1) were tested for European corn borer. Bucket traps consist of a bucket where pheromone attracted males are poisoned by a volatile insecticide (dichlorvos=Vapona). Two bucket trap designs were tested the Universal Moth Trap (also known as International Pheromone System; IPS) (Bartels and Hutchison 1998, Reardon et al. 2006), and the Multipher trap (Ngollo et al. 2000). Despite these traps being efficient at trapping various lepidopteran pests [*Spodoptera exigua* (Hübner), Lopez 1998; *S. nonagrioides*, Ameline and Frerot 2001], they performed poorly in trapping European corn borer, and they were rapidly abandoned with a few exceptions (Gemeno et al. 2006).

Sticky traps are prevalent in many pheromone-baited trap studies. In sticky traps, male moths are captured by becoming entangled on a glued surface. Included in this category are home-made traps made from glue-coated milk boxes (Starratt and McLeod 1976, McLeod and Starratt 1978, Kennedy and Anderson 1980), cylindrical cardboard containers (Kennedy and Anderson 1980), or other materials (delta shaped Tetra traps used in Peña et al. 1988) and commercial designs such as wing traps (Pherocon 1-C: Fletcher-Howell et al. 1983, Durant et al. 1986, Webster et al. 1986, Thompson et al. 1987; Traptest: Maini and Burgio 1990) and delta traps (INRA-Bioprox traps: Stockel 1980, Pelozuelo and Frerot 2006). Because differences in the efficiency of various sticky trap designs have been documented for other moths [*Cydia pomonella* (L.): Fadamiro, 2004; *Pectinophora gossypiella* (Saunders) Athanassiou et al. 2002] it would be interesting to compare sticky designs for the capture of European corn borer, but to our knowledge, the only efficiency comparison available is the study by Kalinova et al. (1994) where wing-traps are shown to be ≈2 times as efficient as delta traps. More attention has been paid to comparisons of sticky traps with other designs. Captures obtained with the Pherocon 1-C design are lower than the captures obtained in water pan traps (Thompson et al. 1987). In Pherocon 1-C (Durant et al. 1986, Webster et al. 1986), Traptest (Maini and Burgio 1990), Scentry wing trap (Stewart 1994), and INRA-Bioprox sticky traps (Pelozuelo and Frerot 2006), captures are lower than captures in mesh cone traps. When the behavior of males approaching a trap is observed, results always indicate that sticky traps are as efficient as the other designs at attracting male but far less efficient at capturing them (Webster et al. 1986, Thompson et al. 1987, Pelozuelo and Frerot 2006). Webster et al. (1986) found that 19% of males approaching within 25 cm of the Pherocon 1-C trap were entangled. Thompson et al. (1987) observed that only 8% of males within 50 cm of the Pherocon 1-C trap were captured, whereas in Pelozuelo and Frerot (2006), the proportion of males caught was <3% of males approaching within 45 cm of the INRA-Bioprox trap. Improving sticky trap efficiency has been explored using different types of glue (McLeod and Starratt 1978) or by coating the inside upper part of the traps (Webster et al. 1986). Different glues showed differences in trapping efficiencies, but none

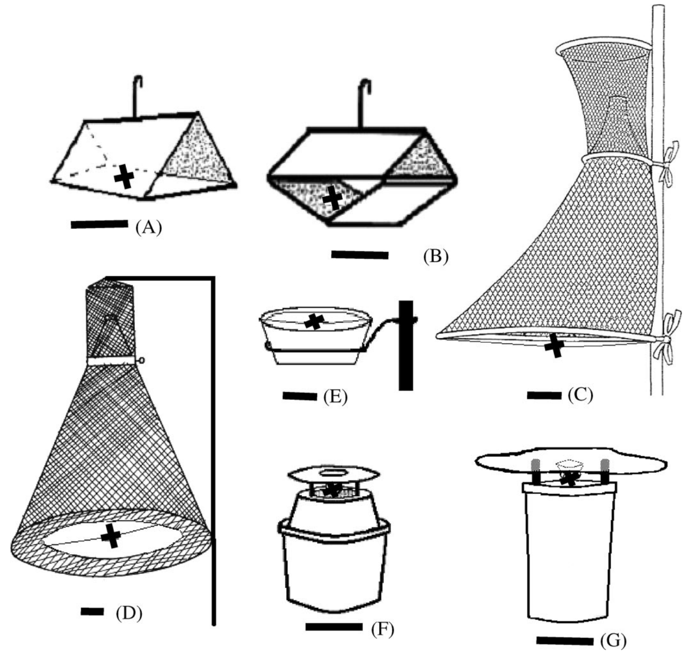

Fig. 1. Pheromone-baited traps tested for capture of European corn borer males. (A) Sticky delta trap. (B) Sticky wing trap, Pherocon 1-C. (C) Nylon mesh cone trap, Scentry design. (D) Wire mesh cone trap, *Heliothis* trap design. (E) Water pan trap. (F) Bucket trap, IPS design. (G) Bucket trap, Multipher design (see text for references). Black cross represents the position of the pheromone cap. Black bars under the trap represent ≈10 cm. Drawing C is from a technical bulletin edited by Scentry Inc.

of these modifications of sticky traps improved moth capture to levels as high as in a mesh cone trap.

Water pan traps and mesh cone traps are the most efficient traps for capture of the European corn borer male moth. Water pan traps are plastic pans filled with a detergent solution in which moths drown (Fig. 1) (Thompson et al. 1987, Gray et al. 1991, Stewart 1994). In such traps, the pheromone bait is suspended on a wire just over the water surface. Moth catches in water pan traps are higher than those in bucket traps (IPS design: Bartels and Hutchison 1998) and in sticky traps (Oloumi-Sadeghi et al. 1975, Thompson et al. 1987); equal to captures in Scentry nylon mesh cone traps (Bartels and Hutchison 1998, Ngollo et al. 2000) and lower than those in *Heliothis* traps (Bartels and Hutchison 1998). However, water pan traps are less convenient as they require regular refilling and as many untargeted insects or even small vertebrates can get trapped.

Mesh cone traps consist of a cone made of mesh. They perform like a bow net: attracted moths enter the trap through the underside and then they cannot find their way back out and end up in a capture bag (Fig. 1). Three main versions of mesh cone trap exist, and their nomenclature sometimes overlaps. The Hartstack trap was initially developed for the capture of *Heliothis* moths by Hartstack et al. (1979), and it is also referred to as *Heliothis* trap or Texas trap. It is made of a rigid metal wire mesh. The others two mesh cone traps are made of nylon, one of which is referred to as the Scentry trap (Scentry Biological Inc., Billings, MT) or exceptionally as the *Heliothis* trap, and the other trap as the Coretrap, marketed by the agency Riff 98 (Bologna, Italy). A modified boll weevil trap that can be related to the mesh cone trap based on its capture technique was tested by Durant et al. (1986), but it did not catch any moths. The use of Hartstack trap for European corn borer capture was first reported by Webster et al. (1986). Their comparison with sticky trap design and further work by Maini and Burgio (1990) and Pelozuelo and Frerot (2006) demonstrated that mesh cone traps are far more efficient than sticky traps, total capture being increased by a factor of 6–9. This difference is due to a better capture rate, because it ranges from 31 to 72% of males attracted close to the mesh cone traps versus from 3 to 19% in delta traps (Webster et al. 1986, Pelozuelo and Frerot 2006). In mesh cone traps, captures are more variable than in sticky traps during the season (i.e., they have a greater standard deviation), and they commonly peak at 50–100 males per night per trap (Bartels and Hutchison 1998, Bartels et al. 1999, Pelozuelo and Frerot 2006). The amplitude of variation for capture in mesh cone traps is also higher than for sticky traps, for which captures are rarely >30 males per night per trap, probably due to a saturation of the glued surface as reported for *P. gossypiella* (Beasley and Adams 1994). Consequently, captures in mesh cone traps are easier to interpret than captures in sticky traps. Although Goodenough et al. (1989) initially thought that the Hartstack cone trap would not be of interest for monitoring moths because of high

Table 1. Recommendations made by firms selling European corn borer pheromone bait about the trap design to use for catching males

Recommended trap type	Crop protection firm selling European corn borer pheromone[a]	
	% (*n*)	Firm name (country)
Mesh cone trap only	7.7 (2)	Riff 98 (Italy), Great lake IPM Inc. (U.S.A.)
Mesh cone trap and sticky trap	7.7 (2)	Gempler's (U.S.A.), Scentry Biological Inc. (U.S.A.)
Sticky trap only	30.8 (8)	Pherotech International Inc. (Canada), Agrisense-BCS Limited (England), Biosystemes France s.a.r.l. (France), SCAM (Italy), Isagro s.p.a. (Italy), Serbios s.r.l., (Italy), Intrachem Bio Italia s.p.a. (Italy), Suterra LLC (U.S.A.)
Sticky trap and bucket trap	19.2 (5)	Chemtica Internacional s.a. (Costa Rica), Novagrica Hellas s.a.(Greece), Chemia s.p.a. (Italy), Atlas Agro (Switzerland), Trc Inc. (U.S.A.)
Bucket trap only	11.5 (3)	Bioplanet s.c.a. (Italy), Flore Salud Control de Plagas Canarias (Spain), Econex (Spain)
None	23.1 (6)	Biobest n.v. (Belgium), Oecos Ltd. (England), Syngenta Bioline Ltd. (England), Trifolio-M GmbH (Germany), Novapher s.a.s. (Italy), Hercon Environmental (U.S.A.)

[a] Information was retrieved from the websites of the companies, after searching for websites of well-known companies, company names from Jones (1998), and also by using following key words: *Ostrinia*, pheromone, trap, corn borer, taladro del maiz, trampa, trappola, trappole, and piralide (Google as search engine).

costs and difficulty in handling, cheaper nylon mesh versions are now available (Scentry trap and Core-trap), and they are in use in the United States and Europe. Nevertheless, it must be highlighted that many firms selling European corn borer sex pheromone continue to provide nonupdated recommendations for trap use (Table 1). Of 26 firms found on the Web, 16 recommend the use of bucket traps, sticky traps, or both; two firms state that both sticky and mesh cone traps can be used; and two firms recommend only the mesh cone trap. Six firms do not make any recommendations.

Optimization of Trap Placement

Trap placement relative to surrounding vegetation, crop fields, and windbreaks can alter trap efficiency. At a trapping site, the height of the trap influences capture performance. Stockel (1980) considered that delta traps are optimally placed if their height is adjusted to corn canopy height. Among three positions tested (80, 240, and 400 cm above the soil surface), he showed that during the first flight, when corn stem size is 30–100 cm, only the traps hung at 80 cm captured male moths. Conversely, during second flight, most captures were achieved at a height of 240 cm. At 400 cm, almost no capture could be obtained (<10 moths per trapping season). A similar observation of trap height influence was made by Welty (1995) and tested by Mason et al. (1997) with the wire mesh cone trap. The placement of this trap was shown to be optimal with the base of the trap being placed approximately at 10 cm below the top of the surrounding vegetation, captures then being a factor of 3.83 greater than those in traps placed 50 cm above canopy.

At the landscape scale, traps should be placed in grassy areas bordering the crop fields, which may host or attract the population of adult moths. Such sites are reputed to be aggregation sites for female and male moths seeking mates (Showers et al. 1976, Derozari et al. 1977). Therefore the sexually motivated attraction of males to the pheromone bait should be particularly efficient at this type of site. Fletcher-Howell et al. (1983) first noticed that traps placed in an area on which vegetation is sparse and short caught fewer moths compared with traps placed in 91–120-cm-high vegetation. However, only a few subsequent studies focus on this question. Welty (1995) mentions that proximity of the wire mesh cone trap to vegetation is important for European corn borer capture. Derrick et al. (1992) compared the performances of traps placed inside potato (*Solanum* spp.), corn, and cotton, *Gossypium hirsutum* L., fields or outside in grassy borders. In this study, significant differences among positions in the crop (when any) were always in favor of the within-field trap placement, with traps capturing more moths inside the crop than in the grassy border. Work by Ngollo et al. (2000) led to a similar conclusion when comparing grassy borders, first corn plant rows and mid-field as trap positions. Furthermore, because their work included a temporal aspect, it was shown that in early flight periods, more moths were captured in grassy borders and first rows than within fields. This relationship was reversed during peak periods, and similar levels of capture were obtained in both locations during the postpeak period. From our own experience, we consider that the best place to obtain high capture levels may vary strongly according to agrosystem characteristics (e.g., crop type, crop phenological stage, and weed presence inside field). For example, in southern France, cornfields during the first flight of European corn borer are almost bare surfaces with only 15–100-cm-high corn plant rows, and thus they cannot be used as aggregation sites by the moth. The situation is completely different during the second flight, when the moth can be encountered in fully grown corn and weed patches inside the fields.

Reardon et al. (2006) showed that in high and moderate wind speed conditions, traps perform better when positioned on the leeward side of windbreaks, rather than on the windward side or in the absence of windbreaks. In low wind conditions, captures are greater at sites far away from windbreaks, even if not

Table 2. Correlation between male + female European corn borer capture in blacklight trap (X) and male European corn borer capture in pheromone-baited mesh cone trap (Y). Numbers of paired capture (N pair) and linear regression characteristics are given (slope, intercept, r^2 Pearson, Student's t statistic observed [t_{obs}] and expected [t_{exp}] at the significance level of 5% for the null hypothesis that $r = 0$)

Data set[a]	County	Yr	N pair	Slope	Intercept	r^2 Pearson	t_{obs}	t_{exp}	Result
Ohio	Franklin	2005	20	0.19	1.52	0.251	2.45	2.10	$r^1 \neq 0$
		2004	22	1.22	7.36	0.053	1.06	2.09	$r = 0$
		2003	16	1.11	10.91	0.055	0.90	2.15	$r = 0$
		2002	19	−0.22	33.14	0.017	0.54	2.11	$r = 0$
		2001	17	0.45	6.86	0.191	1.88	2.13	$r = 0$
	Sandusky	2005	17	0.22	3.13	0.293	2.49	2.13	$r^1 \neq 0$
		2004	18	0.11	6.03	0.018	0.54	2.12	$r = 0$
		2003	16	0.48	12.66	0.106	1.29	2.15	$\mathrm{r} = 0$
		2002	18	0.16	16.67	0.198	1.99	2.12	$r = 0$
		2001	13	0.16	3.13	0.357	2.47	2.20	$r^1 \neq 0$
		2000	20	0.25	9.96	0.183	2.01	2.10	$r = 0$
		1999	17	0.27	−1.15	0.758	6.85	2.13	$r^1 \neq 0$
	Wood	2002	21	0.03	6.68	0.333	3.08	2.09	$r^1 \neq 0$
Kansas	Finney	2002a	13	0.26	−0.57	0.934	12.46	2.20	$r^1 \neq 0$
		2002b	77	0.27	0.70	0.680	12.62	1.99	$r^1 \neq 0$
		2001	86	0.19	2.45	0.161	4.01	1.99	$r^1 \neq 0$
		2000	45	1.31	3.49	0.068	1.76	2.02	$r = 0$
		1999	58	0.68	4.69	0.394	6.03	2.01	$r^1 \neq 0$
		1998	43	0.01	7.44	0.000	0.05	2.02	$r = 0$

[a] Data sets were provided by Laurent Buschman (Kansas State University) and Celeste Welty (The Ohio State University). Most of them are available on the following websites: http://www.oznet.ksu.edu/swao/entomology.htm (Kansas State University Research and Extension); and http://ipm.osu.edu/traps/01vegrpt.htm#ecbb (The Ohio State University Extension). Nonpaired data were excluded from the original table before calculations. Traps were placed close to corn or pepper crop. Distance between BLT and PBT was ≈45–180 m in Kansas and 300–700 m in Ohio.

significantly higher than captures obtained on the leeward side of the windbreaks.

Comparison of Pheromone-Baited Trap and Blacklight Trap Monitoring Techniques

Because the main purpose of pheromone-baited traps is to substitute for blacklight traps, many comparisons have been made of these monitoring methods, based on two major criteria: total capture and temporal pattern of capture. Regarding total capture, pheromone-baited sticky traps give poor results. In Starratt and McLeod (1976), 15 sticky traps are necessary to catch as many European corn borer males as one BLT, and Kennedy and Anderson (1980), also facing unsatisfactory results with sticky traps, concluded that BLT are preferable. However, wire mesh cone traps are able to catch the same number of male moths per night and per trap as BLT (Welty 1995, Bartels and Hutchison 1998, Bartels et al. 1999). However, even if capture level can be equivalent when the wire mesh cone trap is used (i.e., the most efficient design among PBT), the temporal dynamics of capture recorded with PBT and BLT are different. When comparing data sets of European corn borer capture achieved in BLT and PBT, it is obvious that the relationship between BLT and PBT is highly fluctuating. The correlation index r is significantly different from zero (i.e., there is a significant correlation between PBT and BLT captures) for <50% of 19 capture data sets collected and analyzed from the Web (Table 2). It is generally considered that BLT and PBT do not reveal the same depiction of ongoing flight, because they are based on a different type of attraction. Because PBT and BLT captures evolve differently at low population densities or when mated females are the majority among females, Oloumi-Sadeghi et al. (1975) suggested a competition hypothesis in which the pheromone bait and calling European corn borer females are pheromone sources "competing" for the attraction of males. Studying *Heliothis* (now *Helicoverpa*) *zea* (Boddie), Roach (1975) argues that in high population conditions, pheromone baits are less efficient because of a higher probability of males meeting a calling female rather than the trap. This hypothesis has been often cited for European corn borer (Kennedy and Anderson 1980, Fletcher-Howell et al. 1983, Durant et al. 1986, Thompson et al. 1987, Bartels and Hutchison 1998, Bartels et al. 1999). Even though Thompson et al. (1987) found that BLT and PBT captures are significantly correlated when total captures in BLT are <300 moths per week, correlation is lost at higher moth density, we consider that the problem is still not solved. Examining 376 pairs of BLT and PBT captures (obtained from the 19 capture data sets listed in Table 2), we found positive and significant correlation coefficients both at low (<25 moths per night per BLT) and high moth densities (>200 moths per night per BLT) (Table 3). At intermediate densities, correlation coefficients were not significant, and slope could be either positive or negative.

Regarding the key stages of moth phenology, both PBT and BLT detect the flight onset at approximately the same time, but flight peak dates obtained from PBT are always delayed compared with those in BLT. The delay lasts from 4 d up to 15 d (Oloumi-Sadeghi et al. 1975; Kennedy and Anderson 1980; Durant et al. 1986; Bartels et al. 1997, 1999; Bartels and Hutchison 1998). Furthermore, Oloumi-Sadeghi et al. (1975) point out that male moth capture in PBT peaks after most of the female moths are observed to shift from a preoviposition physiological status

Table 3. Correlation at various moth densities between male + female European corn borer capture in blacklight trap (X) and male European corn borer capture in pheromone baited mesh cone trap (Y)

Density[a]	N pair	Slope	Intercept	r^2 Pearson	t_{obs}	t_{exp}	Result
$0 < d \leq 25$	257	0.86	4.10	0.085	4.85	1.960	$r^1 \neq 0$
$25 < d \leq 50$	45	0.25	10.32	0.008	0.60	2.021	$r = 0$
$50 < d \leq 75$	21	−0.86	75.79	0.048	0.98	2.093	$r = 0$
$75 < d \leq 125$[b]	25	0.32	−2.06	0.017	0.63	2.069	$r = 0$
$d > 125$	28	0.16	5.46	0.247	2.92	2.056	$r^1 \neq 0$
$0 < d \leq 50$	302	0.42	6.67	0.078	5.03	1.960	$r^1 \neq 0$
$50 < d \leq 100$	28	−0.23	39.61	0.019	0.71	2.056	$r = 0$
$100 < d \leq 150$	23	−0.77	118.62	0.056	1.11	2.080	$r = 0$
$d > 150$	23	0.14	15.68	0.182	2.16	2.080	$r^1 \neq 0$
$0 < d \leq 100$	330	0.28	8.02	0.081	5.37	1.960	$r^1 \neq 0$
$100 < d \leq 200$	29	0.42	−15.48	0.051	1.21	2.052	$r = 0$
$d > 200$	17	0.19	−17.27	0.326	2.69	2.131	$r^1 \neq 0$

Numbers of paired capture (N pair) and linear regression characteristics (slope, intercept, r^2 Pearson, Student's t statistic observed [t_{obs}] and expected [t_{exp}] at the significance level of 5% for the null hypothesis that $r = 0$) are given.

[a] The density indicator is the number of males and females captured per blacklight trap per night. The 376 pairs of BLT and PBT capture originate from the 19 data sets cited in Table 1.

[b] Data were pooled because of low number of pairs for $75 < d \leq 100$ and $100 < d \leq 125$ if considered separately.

to a postoviposition status. The counting of egg masses deposited on crops confirms that male captures in PBTs peak only after the oviposition peak in the field.

Other studies (Kennedy and Anderson 1980, Durant et al. 1986, Bartels and Hutchison 1998, Bartels et al. 1999) also compare PBTs and BLTs, but the capture of females in BLTs (because information on its own or through the determination of female physiological status [Oloumi-Sadeghi et al. 1975, Maini and Burgio 1999, Xingquan et al. 2004]) is not cited in the discussion despite that it may be an important argument in choosing BLTs versus PBTs.

Information Lacking about European Corn Borer Monitoring with Pheromone-Baited Traps

Studies with pheromone-baited traps started in the early 1970s. Great progress was made in providing a pheromone-baited trap efficient at attracting and capturing European corn borer males; currently, such traps are widely used by extension entomologists seeking guidance on treatment application. However, numerous questions raised during this research still have no conclusive answer. The most important question is that it is still unclear whether PBTs accurately describe moth phenology. Fletcher-Howell et al. (1983), Bartels et al. (1997, 1999), and Bartels and Hutchison (1998) repeatedly highlight that no well-defined relationship has been shown between trap count and either egg mass deposition or infestation level. Legg and Chiang (1984) found no significant correlation between European corn borer male capture in PBT and egg mass deposition in the monitored cornfields. In contrast, Derrick et al. (1992) and Ngollo et al. (2000) found a significant correlation between PBT capture and egg mass deposition. Ngollo et al. (2000) also found a correlation between PBT capture and corn leaf damage, as did Maini and Burgio (1999) between PBT capture and corn ear infestation, but the latter studies considered male capture as "not completely reliable" for monitoring European corn borer larval damage. In France, Stockel (1984) concluded a 2-yr survey of larval load in corn stalks in relation to PBT capture by noting that PBTs should only be used to detect the onset of the moth flight, not to predict damage. Stockel considers that such information is valuable to initiate field scouting for egg masses but that it cannot satisfy other expectations such as predicting population levels and establish thresholds for treatment.

Further work also is required to investigate the competition hypothesis, which may account for difficulties in correlating male capture with egg mass deposition or crop damage. Various laboratory experiments have shown that males are highly attracted to synthetic bait, but few behavioral data are available to test the competition hypothesis. Male behavior in choices between a female and a source of synthetic pheromone is unknown in field conditions, as are the attraction, stimulation, and sampling range of a PBT (attraction range being "the maximum distance over which insects can be shown to direct their movement to the source" according to Wall and Perry (1987); also see this reference for the others definitions). Pelozuelo (2004) showed that males fly equally or prefer the pheromone lure when allowed to chose in a wind tunnel between a rubber cap loaded with 100 μg of synthetic pheromone and either one or two calling females, each pheromone source being 8 cm apart. No field experiment yet performed has been designed to explore the competition hypothesis. Manipulation of the female density (through capture of females and release of additional females in aggregation sites) may make it possible to test this hypothesis, complemented with a modeling approach.

Because pheromone trapping works on behavior manipulation principles, it is also important to remember that European corn borer behavior and ecology must be well known and taken into account in trapping procedures. Specifically, the "aggregation: of moths should be further investigated. Actually, this term is used ambiguously because the mechanism determining the spatial distribution of the moth is unknown, except some preference for grassy areas (Pleasants and Bitzer 1999). Furthermore, efforts to understand behavioral mechanisms leading to the aggregated distribution would be valuable for improving not only European corn borer pheromone trapping but also management strategies of European corn borer resistance to genetically modified crops.

Conclusions

Based on the literature, the PBT may be a valuable tool for decision-making purposes in the framework of European corn borer management. Its specificity, ease of use and monitoring, and relatively low cost make it an attractive alternative to BLT and other monitoring techniques. The effort dedicated to its optimization has produced efficient baits, efficient traps, and good trapping procedures, which are now available for researchers and extension entomologists who want to monitor the pest.

However, the value of the information PBTs can provide may not be as high as expected. It remains unclear whether flight curves plotted from PBT captures truly reflect moth phenology. This point has been repeatedly raised (Fletcher-Howell et al. 1983; Bartels et al. 1997, 1999; Bartels and Hutchison 1998), but no study has been specifically designed to address the question. As long as it remains unresolved, PBTs can be useful in complementing other monitoring techniques, but they cannot completely replace them at present without a potent risk to compromise the crop protection strategy. Kennedy and Anderson (1980) and Stockel (1984) already highlighted limits of the PBT regarding the purpose of positioning a treatment date that matches the moth phenology.

Specific experiments should be designed to assess moth phenology directly in the field through a combination of caged larvae surveying, moth counting in aggregation sites and egg mass scouting, in relation with pheromone-baited trap data. In the laboratory, a modeling approach should be applied to determine the likelihood of a pheromone trap catching a European corn borer male in the different stages of moth flight and at different female densities.

Acknowledgments

We thank Gilles Genestier and Yvelines Querou from the French National Institute for Agronomic Research who helped locate essential references. We also thank David Bartels and Celeste Welty (The Ohio State University) for helpful comments and improvement of the first version of this text. We thank Lawrent Buschman (Kansas State University) and Celeste Welty from for permission to use PBT and BLT capture data. This work was supported by the French Academy for Agriculture (Académie Francaise d'Agriculture) and the Japanese Society for the Promotion of Sciences.

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Received 15 August 2006; accepted 4 March 2007.